Evaluation of local site effects on high frequency earthquake motion by an inversion method(地震動のインバージョン解析に基づく高振動数領域の地盤増幅特性評価)

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論　文　内　容　要　旨

Since the observation of strong ground motion was initiated in 1953, several destructive earthquakes have periodically occurred in Japan, such as the 1964 Niigata event ($M=7.5$), the 1968 Tokachi-oki event ($M=7.9$), the 1978 Miyagiken-oki event ($M=7.4$), and so on. These events have clearly shown that local site effects have greater influences on structural damage than previously thought. Although our knowledge on local site rffects has increased drastically owing to various developments in instrumentation, theory, computers and other advanced technology, estimating site effects is still in developing stage particularly in high frequency range, bacause of the complicated phenomena caused by diverse geologic materials and irregularly shaped near-surface structures. Because all our engineering strucures are constructed on these complex near-surface media, understanding of local site effects on strong ground motions is of particular importance for mitigation of earthquake disaster as well as earth-quake-proof design.

Ultimate goal of this thesis is to establish an approach for estimating site effects from seismic bedrock. Attentions were confined to high frequency range from 1 to 10 Hz, because

the predominant frequncies of structures are included in the range, but quantitative estimation of local site effects has not been achieved. The present thesis begins with the review of obsarvation history of strong ground motions and the review of state of the art on site effect studies (Chapter 1 : General introduction). It is concluded from the review that the most suitable approach to attain the goal is to empirically evaluate local site effects on the basis of abundant observed data. Both strong motion spectra of body waves and coda waves from local earthquakes were used to assess the site effects in different geological conditions.

The most important result obtained in the present thesis is that the site amplification factors from seismic bedrock with shear-wave velocity of about 3 km／sec were successfully evaluated without knowing the detailed information on the subsurface structure beneath the stations. Site effect estimations from the seismic bedrock had been a significant task, but rarely achieved except for a few studies utilizing very deep borehole observations. The succes in the present thesis is primarily attributed to incorprating inverse technique into site effect estimations.

Another important result is that coda waves from local earthquakes are also applicable for evaluating site amplifications for *S*-waves. This is a powerful and alternative method when strong motion records are not available due to, for instance, short term of strong motion measurement. This finding will drastically improve our knowledge on local site effects because of a rich supply of data covering wide region.

The main body of this thesis consists of the following five chapters.

Chapter 2 Simultaneous separation of source, path, and site effects from strong motion spectra by an inversion method

Source, propagation path, and local site effects in observed horizontal strong motion spectra are separated by an inversion method for the purpose of empirically estimating local site effects in different geological conditions. Analyzed data are the direct *S*-wave portions of 167 horizontal records observed at 7 stations including deep borehole sites. A station where granitic rock is outcropped is assigned as the reference station, and its site amplification is constrained to 2 assuming flat response. The inverted site amplifications at deep borehole stations are compared with the theoretical transfer functions from the seismic bedrock to the observation points. Good agreements are shown lower than about 6 Hz, indicating that the site amplification factors from the seismic bedrock can successfully evaluated up to the frequency. At the same time, a concern is rasied that the constraint may not be adequate higher than 6 Hz because the flat response assumption is no longer valid in the frequency range at the reference station.

Chapter 3 Site effect estimation from seismic bedrock

The problem on the constraint higher than 6 Hz is resolved through re-examining observed spectra at the reference station. The discrepancy indicated in Chapter 2 is primarily attributed to the topographical effect at the frequency range at which the incoming wave lengths are compatible to or less than the dimension of geographical features around the reference station. The inversion is redone using the same data set but the revised constraint considering the site-specific characteristics higher than 6 Hz at the reference station. The inverted site amplifications show excellent agreements with the theoretical transfer functions up to 10 Hz. The agreement indicates that this empirical approach is one of the most practical methods of evaluating site effects from seismic bedrock, provided that a reliable constraint is applied like this thesis.

Chapter 4 Horizontal site amplification factor of S-waves in special relation to surface geology

A quantitative relation between surface geology and site amplification is derived, as an application of the inversion analysis established in Chapter 3. The analyzed data are direct *S*-wave portions of 327 horizontal accelerograms at 19 stations in different geological conditions from Cretaceous to alluvial. This data set is expanded from Chapter 3 by adding the strong motion records over a wide region. The observation stations are classified into 5 groups based on their surface geologies. There are obvious differences among the site amplification factors of these groups in the frequency range from 1 to 5 Hz, and the differences strongly depend on shear-wave velocity of the surface stratum of the stations. This finging indicates that variations in impedance are responsible for the differences in amplification factors. The degree of the dependence on the shear-wave grows weak at most stations on the sedimentary strata as frequency increases from 5 to 10 Hz, which may be due to the effect of near-site attenuation. These results will provide a fundamental information for improving the quality of seismic zonation necessary for the mitigation of earthquake disaster.

Chapter 5 Vertical site amplification of S-waves

Site effects of vertical components are examined, as another application of the inversion analysis established in Chapter 3. Vertical strong motion spectra for time windows after the onset of *S*-waves are analyzed. This is the same station-event pairs used in Chapter 2. The first finding in this chapter is that the inverted source and path effects from the vertical spectra show similar amplitudes and frequency dependency to those from the horizontal spectra. This finding indicates that the incident spectra to the seismic bedrock are similar in the two components. Second, the factors of vertical and horizontal site amplification show different amplitude. This finding indicates that the wave propagation processes above the seismic bedrock are different in the two components. Third, the vertical site effects at deep borehole stations can be approximately explained by the oblique incidence of plane *SV*-waves to the seismic bedrock. From these findings, it is finally concluded that the vertical seismic waves after the onset of *S*-waves are possibly generated at the source as *S*-waves and propagating to the seismic bedrock also as *S*-waves. Then they are converted to *P*-waves above the bedrock.

Chapter 6 Site amplification from coda waves

Coda and *S*-wave site response are evaluated using a total of 708 three-component waveforms observed at four TERRA scope stations in southern California. After verifying that the coda decay curves are independent of event-station pairs considered, the coda site amplifications are first estimated by spectral ratio method for the lapse time windows after 70 sec from the earthquake origin time. Second, *S*-wave site amplifications are evaluated by an inversion method using the direct *S*-wave portions of the same waveforms. It is found that the coda site response shows a good agreement with *S*-wave site response for both horizontal and vertical components, justifying the use of coda waves in determining site-specific amplification. This agreement is expected because the coda waves are dominated by *S*-waves as theoretically suggested by the recent work. The findings in this chapter make clear that coda waves can be applicable in determining site-specific amplications for *S*-waves.

Chapter 7 Conclusions and future direction of research

Major conclusions from the preceding five chapters are summarized, and future directions of research are suggested.

審査結果の要旨

地震動の特性に及ぼす局所的地盤特性の影響を解明することは，構造物の地震被害の解明や耐震設計における入力地震動の設定を行う上で極めて重要である。

本論文は，多地点で同時観測された地震記録のインバージョン解析に基づき，地震基盤上の表層地盤による地震動スペクトルの増幅特性を求め，地盤の種別及びせん断波速度と増幅特性の関係を明らかにしたもので，全7章からなる。

第1章は序論である。

第2章では，東北及び関東地方の7観測地点で20の地震により得られた167の地震波形記録を用い，地盤増幅特性の検討を行っている。即ち，インバージョン法に基づいて，地震波の主要動水平成分の高振動数域（1-10Hz）におけるフーリエスペクトルを震源スペクトル，伝播経路の減衰特性及び地盤増幅特性に分離し，地震基盤が露頭していると考えられる基準観測地点の増幅特性を一定値として，各地震毎に地震基盤上の表層地盤増幅特性を求め，地中地表同時観測による伝達特性及び理論的な成層地盤伝達特性との比較検討を行なっている。

第3章では，地震基盤上の基準観測地点の増幅特性について再検討し，6Hz以上において周波数と共に減少する新たな増幅特性を仮定することにより，理論値と極めてよく一致する妥当な結果が得られることを示している。

第4章では，前章で得られた結果に更に12地点の強震記録による結果を付け加えて，水平動の地盤増幅特性と地盤種別及びせん断波速度との関係を検討し，白亜紀花崗岩地盤では2－3，白亜紀から古第3紀の堆積岩地盤では2－6，新第3紀地盤では5－20，洪積地盤では8－30，沖積地盤では40程度の増幅率となることを明らかにしている。

第5章では，同様の手法により主要動の上下成分について地盤増幅特性を求め，水平動の場合と比較するとともに，増幅特性と地盤性状との関係を示している。

第6章では，米国南カリフォルニアの多点地震観測記録に基づき，地震波終末部のコーダ波を用いて地盤増幅特性を求める新しい方法を示し，主要動部分による増幅特性とコーダ波部分による増幅特性が良く一致することを明らかにしている。

第7章は結論である。

以上要するに，本論文は実地震記録の解析に基づいて地震動特性に及ぼす地盤性状の影響を実証的に解明したもので，建築学及び地震工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。